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Burden sharing, joint implementation, and carbon coalitions

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The burden-sharing problem

Negotiations over global warming abatement strategies are focused on abatement by OECD states. Unfortunately, abatement opportunities within the OECD are quite costly relative to the abatement opportunities available in many non-OECD countries. Acceptance of this fact has lead many observers to conclude that joint implementation (JI) should be included as one component of any multilateral agreement.[1] Current discussions amongst negotiators appears to accept the idea of joint implementation within the set of nations party to an agreement to abate, which we take here to be the OECD. It remains an open and controversial issue if this will be extended to include abatement undertaken by countries that are not party to the agreement.

We assess how joint implementation affects the costs of abatement and the allocation of the burden of abatement among OECD member states. We also explore the implications of emission trading and JI for a fair distribution of the burden across OECD countries.

Our most important conclusion is that the problem of sharing the burden equitably is significantly less difficult *if emission rights are tradeable*. When emission rights are not tradeable then it can be very difficult to find the right way to share the burden, and there can be considerable variations in the distribution of the burden which may be politically unacceptable. With the right combination of policies with respect to JI and tradeable rights, the gains from trade in carbon abatement are distributed in such a way as to mitigate the global equity problem that arises from an OECD commitment to abate. In effect, efficiency *can* be the

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C. Carraro (ed.), International Environmental Agreements on Climate Change, 77–108.

handmaiden of solving the burden sharing problem. Rather than there necessarily being a trade-off between efficiency and equity, the two can be complementary in designing an attractive global warming policy.

We draw this conclusion from simulations of a large-scale computable general equilibrium (CGE) model of global trade and energy usage. The model we use is based on the IIAM model developed by Bernstein *et al.* (1997), with extensions to consider tradeable rights, JI and endogenous burden sharing.

The model

Basic features

The IIAM multi-regional trade model[2] is a dynamic general equilibrium model with 25 countries and regions.[3] Each region has an aggregate production function for non-energy goods which produces differentiated products for the domestic and export markets. Factors of production include labor, capital and fossil fuels (oil, gas and coal). Final consumption in each region is composed of domestic goods, imports and fossil fuels. Investment demand arises from a Ramsey formulation in which the representative consumer in a region allocates consumption over time and investment equalizes the present value of capital earnings with the cost of investment.

In many respects the model structure is similar to that of Manne and Rutherford (1991). One non-standard feature of the model relates to the representation of substitution in trade. Here we assume that imports are distinguished by export zone rather than country of origin.[4] The 25 countries and regions are each assigned to one of five export zones: OECD, Asia, centrally planned eastern Europe, Middle East and all other countries. Exports from any two countries in the same export zone are treated as perfect substitutes. In this way a consumer in the USA might distinguish goods produced in the OECD from those produced in Asia; however, the same consumer would notice no difference between goods produced in China and those from South Korea since both are assigned to the same export zone.

The model takes 1992 as a benchmark year and solves in 5-year time periods from 2000 to 2030. In each of these seven periods there are eight traded goods: one non-energy export good from each of five export zones, oil, coal and natural gas. There are domestic markets for domestic non-energy output, domestic non-energy output, domestic non-energy demand, oil, coal, and natural gas. The domestic non-energy demand commodity is an Armington aggregate of domestically produced goods and imports from each of the five export zones. Import tariffs and transportation costs segment domestic and international energy markets, with the international price for each of these homogenous goods determined by the interaction of supply and demand.

Primary factors of production include labor, capital and energy resources (specific factors) for the production of fossil fuels. The resource supplies are calibrated to baseline estimates of fossil fuel production, and elasticities of substitution in energy production are calibrated to specified supply elasticities for each of the fuels. Depletion is assumed to lead to rising fossil fuel prices along the 'business as usual' (BAU) scenario, but the endogenous relationship between depletion rates, fossil energy reserves and resources, and the subsequent fuel production is not modeled. That is, the model does not keep a record of the current stock of oil, coal and gas in each time period.

Fuel production and demand in the reference BAU is calibrated to DOE/IEA production statistics and projections.[5] Price-cost margins for fossil fuels are represented in the model as refining and distribution costs. Armington shares for imports from each of the five export zones are calibrated to base year imports, using the qualitative specification of trade elasticities that we use in Harrison *et al.* (1997).[6]

The representative agent for each region maximizes discounted utility for that region over the model's time horizon. Representative agents in each region have perfect foresight. There is a balance of payments equilibrium over time, and all countries borrow and lend at one world interest rate which is determined endogenously. Saving is determined by inter-temporal utility maximization.

There are no adjustment costs explicitly included, but the model assumes a time-dependent elasticity of substitution between energy and other inputs. This elasticity is adjusted parametrically over time so that the scope for carbon abatement is less costly as time passes. Full input flexibility is achieved in 2010.

Investment achieves intertemporal efficiency since the return on investment is balanced against the cost of capital formation. Investment flows to the region paying the highest return. The marginal productivity of a unit of investment and a unit of consumption is equalized within and across countries. There are no restrictions on financial capital, so rates of return remain uniform across countries. However, energy taxes will effect the global interest rate to some extent.

The model horizon is only 2030. We measure welfare in Hicksian equivalent variations over an infinite planning horizon using the terminal period consumption to approximate welfare impacts from 2031 onward. This welfare calculation is exact if we assume steady-state growth rates in all countries beginning in 2030. Following Manne and Rutherford (1994), we assume a common benchmark rate of return to capital in the base year, and we adopt an assumption of uniform growth and discounting toward the end of the model horizon. These assumptions assure that the model produces limited capital flows along the baseline path, consistent with observed levels of international borrowing. The model is formulated as a non-linear complementarity problem using the GAMS/MPSGE software and solvers described in Rutherford (1995, 1997). Most of the standard features of the model formulation are presented in Appendix B. There are three aspects of the model formulation which are somewhat novel.

Welfare analysis without knowing the gross benefit of abatement

To be able to undertake a welfare analysis we either need to specify gross benefits from abatement or hold the global abatement scenario constant as we vary other things. To avoid needless controversy we opt for the latter approach. Therefore, all scenarios look at a fixed global carbon emission trajectory over the 30-year model horizon.

The only assumption implicit in this approach is that gross benefits of abatement in each region are defined over the level of *global* abatement. Although this assumption is perfectly natural in the case of global warming, it may be that some households are willing to pay different amounts for abatement undertaken by different regions, even if the global level is the same.[7] We simply note this possibility here, and maintain our assumption that gross benefits are defined solely over global abatement.

We therefore treat aggregate OECD abatement obligations as an endogenous variable which is chosen to provide a specific time path of *global* emission over the model horizon. This means that the model formally allows for the welfare cost of leakage to the extent that abatement by OECD countries induces increased emissions in other countries. It is as if the OECD defines it's commitments in terms of global emission reductions, and adjusts the specific percentage reduction from BAU to offset any increases in emission by other countries.

Welfare analysis allowing for aversion to inequality

In order to consider the equity implications of carbon taxes on different countries, we employ a 'cardinalized' welfare index. We do this in order to endogenously compute 'fair' distributions of emission rights across members of a coalition, as explained below.

Specifically, we employ a cardinalization of utility which is consistent with a constant coefficient of inequality aversion, a convenient formulation widely used in welfare economics (Atkinson, 1970; Boadway and Bruce, 1984; Layard and Walters, 1978). The welfare impact on region r is assessed by changes in $W_r = U_r^{1-\rho}/(1-\rho)$, where U_r is a linearly homogeneous consumption welfare index defined over the infinite horizon. Values of ρ ranging from 0 to ∞ provide simple representations of social welfare functions ranging from simple utilitarian up to Leontief–Rawlsian. We specify a range of values for ρ parametrically, and trace out how our conclusions change as we allow for more aversion to inequality across regions.

Endogenous burden sharing

We evaluate alternative ways of allocating emission rights across coalition members. One exogenous allocation rule, called BMKSHR, is equal to base year emission shares. With this allocation rule the emissions allocations for OECD members are formulated as fixed shares of OECD aggregate emissions over time:

$$E_{rt} = \theta_r\, E_t^{OECD} \quad r \in OECD$$

It would be possible to look at allocations that vary over time in keeping with forecast BAU emission shares, but this raises an air of indeterminacy in the field[8] which rational negotiators will avoid. We return to this issue when we comment on our JI results, since there are some legitimate concerns about the choice of reference points for JI.

Our endogenous allocation rule, imaginatively called ENDOG, is determined in order to equalize the present value welfare impact across coalition members. We cardinalize utility to approximate in formal terms what might be meant by 'fair', and we then let the model allocate emission rights within an abatement coalition to share the welfare burden. This is where equity concerns will play a role in our simulations. In simulations with endogenous burden sharing the emission shares are determined to equalize the welfare costs of abatement. Specifically, we impose the constraint that:

$$\frac{W_r^{1-\rho}}{1-\rho} - \frac{\overline{W}_r^{1-\rho}}{1-\rho} = \Delta W^{OECD}$$

where $\overline{W}_r$ is the BAU level of the welfare index for region r. This endogenous allocation of emission rights within the abatement coalition permits us to study the equity implications of carbon taxes on different countries.

Scenarios

All simulations and scenarios assume a *fixed global carbon emission trajectory* over the 30-year model horizon. This trajectory is calculated assuming that BAU emissions for non-OECD countries and OECD emissions fall to 95% of their base year levels in 2005, 90% of their base year levels by 2010, and stay constant thereafter.[9]

The relevant emissions trajectories are displayed in Figure 1 in billions of tons. The BAU trajectory shows the model's baseline projection for global emissions under that scenario. The TARGET trajectory shows the fixed target described above. The aggregate emissions profile of the OECD under BAU assumptions is shown in trajectory OECD_BAU. Finally, *assuming no leakage* we would have the profile OECD_T for the OECD.

In all simulations we endogenously adjust OECD emissions to hold global emissions equal to the TARGET profile. Thus it is correct to think of our carbon abatement scenario as one in which the OECD commits itself to some global emissions target, rather than just some fixed percentage of it's own BAU emissions. In this way we know that global abatement will be the same in all scenarios, and can therefore compare welfare for any given region across scenarios.

Our interest is in burden allocation within the OECD and how this interacts with the use of alternative JI policies. For the most part we will just focus on the politically relevant case in which the coalition consists solely of OECD countries.[10]

We consider five policy scenarios for reducing global emissions. These can be best thought of by drawing a distinction between an *abatement coalition* and a

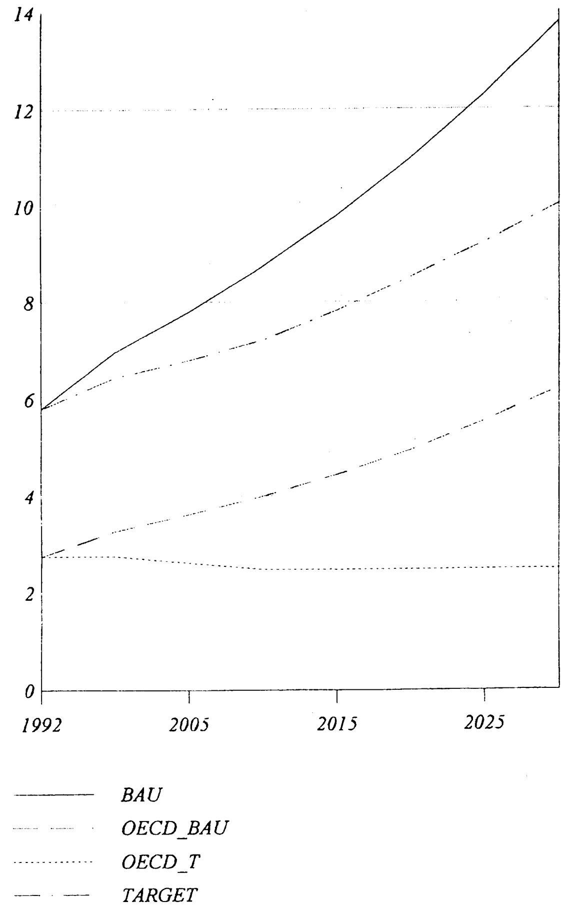

Figure 1. Global carbon emission profiles (billions of tonnes carbon)

JI coalition. The former is the set of countries that agree to *pay* directly or indirectly for abatement. The latter is the set of countries that are legally allowed to *actually undertake* the abatement. These can be distinct sets, and they may not include all countries since some countries may remain outside both the abatement coalition and the JI coalition.

If a country is in the JI coalition then it has a carbon limit imposed and receives payment for doing so. A country that is *only* in the JI coalition does *not* adjust it's abatement endogenously to meet the global abatement target. Thus JI can be viewed in our model as a way of enlarging the coalition of countries that undertake abatement, without requiring all of those countries to initially make commitments to do so. It is not possible for countries only undertaking JI to turn around and purchase JI from another country. Nor would we expect this in equilibrium, since JI will be undertaken by the least cost countries first.

NOTRADE: autarky in abatement

The NOTRADE scenario assumes that regional abatement occurs in an OECD coalition, with *no trading in emission rights*. There are no restrictions on emissions by non-OECD countries, and the inevitable leakage is compensated by stricter reductions in OECD states such that the planned global reduction target is achieved. In effect this is the default in which each country engages in autarky with respect to *direct* trade in carbon emission rights, but allows free trade in carbon-intensive goods. Thus the abatement coalition is the set of OECD countries, and the JI coalition is the null set.

PERMITS: an OECD-only club

The PERMITS scenario assumes abatement in the OECD as in NOTRADE but with tradeable permits *among coalition members*. Non-OECD countries may gain or lose in terms of consumption welfare. The abatement coalition is again the OECD, but now the JI coalition is also the OECD. This corresponds to the OECD setting up a 'JI Club,' and restricting membership to *abatement* coalition members. In effect this can be seen as saying that the reward of agreeing to abate is being allowed to be paid to undertake abatement for others if that is efficient.[11]

For intra-OECD trade in carbon rights there is no essential difference between JI and tradeable permits in our model.

LJI: a not-so-nasty deal

The LJI scenario assumes abatement with *limited joint implementation*. In this scenario, emission allocations to non-OECD countries are reduced proportionally from BAU profiles. Their emission rights are allocated endogenously at levels such that the consumption welfare of non-OECD regions does not *exceed* BAU levels.

In other words, the OECD JI Club offers non-OECD countries the following deal: 'We will let you undertake paid abatement work for us, but we don't want you to get rich doing this work.' So stated it seems a rather harsh deal, and it must be recognized that delicate liberal sensibilities run deep in global warming policy debates. However, if we can anticipate the result in our model that non-OECD countries are *hurt* in welfare terms by the NOTRADE and PERMITS scenarios, the deal sounds much kinder and gentler: 'We are really very sorry that the actions of our coalition have hurt you, so to make you no worse off than you were before our coalition acted we will let you undertake paid abatement work for us.' In effect this scenario defines the abatement coalition as the OECD countries again, but allows the JI coalition to include all countries *if* they agree to not 'profit' in welfare terms from the JI option.

UJI: unlimited joint implementation

The scenario UJI relaxes the constraint in LJI, and allows abatement with *unlimited joint implementation*. Non-OECD countries may now freely sell reductions in emissions below their BAU profile to OECD countries. This scenario defines the abatement coalition as the OECD, and the JI coalition as all countries.

GLOBAL: the holy grail of consensus?

The scenario GLOBAL evaluates the Holy Grail case in which all countries join both the abatement coalition *and* the JI coalition. We do not regard this case as particularly realistic, but it provides a useful reference point.

Results

OECD abatement hurts non-OECD countries

The first major result from our model is that *non-OECD countries suffer drops in welfare when the OECD abates* under NOTRADE and PERMITS. It is no surprise that OECD countries suffer a welfare loss, since they are imposing constraints on their economies. But it may come as a surprise to some that non-OECD countries also lose. The main reason for this result, which echoes a similar finding in Bernstein *et al.* (1997) for a more aggregated version of the model, is that non-OECD countries suffer from the downturn in the OECD.

The loss to the OECD as a whole is about 1.4% of GDP, and the loss for the non-OECD countries is about 0.8% of GDP. Table 1 reports the results for all 25 regions assuming an elastic oil market, and Table 2 reports results with an inelastic oil market.[12] With *inelastic* oil markets there is a relatively *large* drop in the world price of oil, and relatively more leakage through induced goods trade since there is more of a price incentive for non-OECD countries to expand their use of oil. Hence we see from these results that when the price of oil falls more it is possible that some non-OECD countries that are net importers of oil could gain from carbon emission limits in the OECD (e.g., TWN). Of course, some lose since they are net exporters of oil (e.g., MEA).

To understand these welfare effects for non-OECD regions it is useful to think of there being two classes of regions. The major oil exporters lose, of course, since the drop in the price of oil drastically worsens their terms of trade and the value of their endowments. They might gain some of this back as non-abatement countries expand their use of oil, but their use of energy is so small relative to the OECD that this does not offset the initial welfare loss.

The other countries are either minor net exporters of oil or net importers of oil. In the latter case there is a small terms of trade gain with respect to the lower world price of oil. If they are net importers of the non-energy good from the OECD, then they also experience a terms of trade loss on the non-energy side as OECD countries must pass on the increase in the price of their products. They

Table 1. Economic costs of carbon abatement with an elastic oil market

	NOTRADE	PERMITS	LJI	UJI	GLOBAL
Hicksian equivalent change in income (%)					
PLANET	−1.3	−1.1	0.0	−0.1	−0.1
OECD	−1.4	−1.2	0.0	−0.4	−0.1
NOEC	−0.8	−0.7	0.0	0.9	0.2
Billions of dollars per year					
PLANET	−161.3	−139.8	−4.5	−7.9	−6.7
OECD	−137.0	−118.8	−4.5	−34.9	−13.3
NOEC	−24.3	−21.0	0.0	27.1	6.6
AUS	−2.4	1.3	−0.6	−1.7	−0.9
CAN	−5.2	−4.8	−0.5	−1.7	−0.8
EU3	−3.6	−3.2	−0.3	−0.8	−0.4
E_U	−61.5	−53.6	−1.6	−11.4	−4.5
JPN	−18.9	−18.0	−0.9	−4.3	−1.9
NZL	−0.4	−0.4	0.0	−0.1	0.0
USA	−45.1	−40.2	−0.6	−14.9	−4.7
ARG	−0.4	−0.3	0.0	0.1	−0.1
BRA	−0.4	−0.3	0.0	0.3	−0.1
CHL	−0.2	−0.1	0.0	0.1	0.0
CHN	−1.1	−0.9	0.0	5.9	1.2
FSU	−4.3	−4.0	0.0	8.3	4.5
HKG	−0.3	−0.2	0.0	0.1	0.0
IDI	−0.5	−0.4	0.0	1.7	0.5
IDN	−1.1	−0.9	0.0	0.6	0.2
KOR	−0.5	−0.3	0.0	0.6	0.0
MEX	−1.8	−1.5	0.0	1.1	0.4
MYS	−0.7	−0.6	0.0	0.4	0.2
PHL	−0.2	−0.1	0.0	0.1	0.0
SGP	−0.3	−0.3	0.0	0.0	−0.1
THA	−1.4	−1.2	0.0	0.9	0.6
TWN	−0.4	−0.3	0.0	0.3	−0.1
MEA	−4.2	−3.7	0.0	0.8	−0.8
SSA	−1.9	−1.7	0.0	0.6	−0.3
RSM	−1.8	−1.6	0.0	0.7	0.1
ROW	−3.0	−2.6	0.0	4.5	0.3

might gain export market *share* in OECD countries in the non-energy good, but this is more than offset by a reduction in the *scale* of exports to the OECD as final demand in the OECD shrinks after the rise in consume prices of goods.

In general the non-OECD countries suffer in NOTRADE and PERMITS by losing export markets as well as experiencing these terms of trade effects.[13] Reducing the trade elasticities of the model results in slightly larger losses for non-OECD countries: they are less able to substitute away from higher-priced imports coming from OECD countries, and they are less able to expand market *share* in their exports to OECD countries since the latter are less sensitive to price differentials. The default trade elasticities assumed here, 4 for the Armington import–domestic composite elasticity and double that for the imports–imports elasticity, are relatively high in terms of the trade modeling literature.

The region-specific carbon tax rates required to implement these policies in the

Table 2. Economic costs of carbon abatement with an inelastic oil market

	NOTRADE	PERMITS	LJI	UJI	GLOBAL
Hicksian equivalent change in income (%)					
PLANET	–1.8	–1.6	0.0	–0.0	–0.0
OECD	–1.8	–1.6	0.0	–0.3	–0.0
NOEC	–1.8	–1.6	0.0	0.9	0.0
Billions of dollars per year					
PLANET	–231.0	–201.3	–2.4	–3.8	–3.9
OECD	–180.1	–154.9	–2.4	–28.6	–4.1
NOEC	–50.9	–46.4	0.0	24.9	0.2
AUS	–2.7	1.5	–0.8	–1.7	–0.8
CAN	–7.8	–7.1	–1.1	–2.3	–1.2
EU3	–4.5	–4.0	–0.1	–0.6	–0.1
E_U	–81.0	–70.1	0.7	–7.5	–0.1
JPN	–23.0	–21.6	0.8	–2.2	–0.5
NZL	–0.6	–0.6	0.0	–0.1	0.0
USA	–60.6	–53.0	–1.9	–14.3	–2.6
ARG	–0.6	–0.5	0.0	0.0	–0.2
BRA	–0.0	–0.1	0.0	0.6	0.1
CHL	–0.1	–0.1	0.0	0.1	0.1
CHN	–1.3	–1.1	0.0	6.7	1.4
FSU	–6.9	–6.7	0.0	14.7	8.7
HKG	–0.2	–0.1	0.0	0.2	0.1
IDI	–0.1	–0.2	0.0	2.3	0.9
IDN	–2.1	–1.9	0.0	0.2	–0.3
KOR	0.8	0.9	0.0	1.3	0.6
MEX	–3.7	–3.3	0.0	0.4	–0.4
MYS	–1.2	–1.1	0.0	0.2	0.0
PHL	–0.0	–0.0	0.0	0.2	0.1
SGP	–0.2	–0.1	0.0	0.1	0.0
THA	–2.1	–1.8	0.0	1.0	0.7
TWN	0.1	0.2	0.0	0.6	0.2
MEA	–20.6	–19.6	0.0	–7.3	–9.1
SSA	–4.3	–4.1	0.0	–0.5	–1.5
RSM	–4.6	–4.2	0.0	–0.5	–1.2

NOTRADE scenario are shown in Table 3. They are lowest in Australia and the USA, reflecting the greater coal intensity of these countries. In other words, because they use coal so much it is easier for them to meet their abatement targets with relatively small tax incentives. Japan relies much more heavily on nuclear power and has a lower value share for coal which results in a high carbon tax. The E_U is a mix of coal-intensive and nuclear-intensive countries, and as an aggregate region is more like Japan in the sense that it needs relatively high carbon taxes to effect the required abatement.

OECD abatement is easier with joint implementation

The second major result from our calculations is that *the OECD fares much better with either form of joint implementation than with intra-OECD permit trading.* Under limited JI the USA and the E_U actually suffer no significant welfare loss at all, and under unlimited JI their losses are dramatically reduced to less than 0.5%.

Table 3. Carbon tax rates ($ per ton)

	Elastic oil supply			Inelastic oil supply		
	2000	2010	2020	2000	2010	2020
AUS	40	105	110	41	143	195
CAN	143	253	225	147	321	344
EU3	183	389	383	194	502	589
E_U	227	462	450	237	593	686
JPN	170	392	403	183	516	630
NZL	156	404	419	166	520	636
USA	92	208	203	96	270	317
PERMITS	130	294	289	136	381	449
LJI	27	41	36	28	46	43
UJI	27	42	37	29	47	44
GLOBAL	27	41	36	28	46	43

One of the most significant factors in the additional gains under LJI for the USA and E_U is that they actually get to *sell* some emission rights to non-OECD countries, at least up until about 2015. Under UJI they are always net importers of emission rights. Why the difference? Under UJI non-OECD countries are free to offer emission rights relative to their BAU levels, whereas under LJI they are given emissions targets that do not allow them to experience a welfare gain relative to BAU. In effect, under LJI their endowment of tradeable permits is allocated in proportion to their benchmark shares of emissions, but at a fraction of their BAU levels so as to ensure that their welfare does not improve when they start to use those permits (to produce goods or to sell directly to other countries).

There should be no surprise that virtually all of the abatement under the UJI scenario is being undertaken by the Former Soviet Union (FSU) and China (CHN). In percentage terms these trades are also important for these two regions, representing about 4% and 3% of GDP by 2030, respectively. The net welfare gains that these two regions experience are in large measure due directly to the emission rights sales.

The general point here is that the gains from trade in emission rights *within* the OECD are relatively small compared to the gains from trade in emission rights *between* the OECD and non-OECD countries. Joint implementation can be thought of as a type of emissions trade, albeit one undertaken on a bilateral basis. In fact, since the OECD will purchase each unit of abatement from the country with the lowest marginal cost of abatement, and that same country would also be the lowest-cost seller of an extra unit of a tradeable emission right, the two are formally identical in this sense. So the issue here is not so much JI or tradeable permits, as who pays whom to undertake abatement. If the OECD is able to contract with non-OECD countries, the cost of abatement drops significantly.

Joint implementation can be efficient but difficult to implement

Carbon abatement by non-coalition member states poses a significant burden-sharing problem, but *when carbon emission rights can be sold this tension between* *efficiency and equity is dramatically reduced due to joint implementation.* The support for this conclusion comes from comparing the economic costs of the NOTRADE and PERMITS policies with the economic costs of the LJI and UJI policies. Our qualitative conclusion does not depend on whether one assumes elastic or inelastic oil markets in Tables 1 and 2, although the quantities certainly do.

The logic of this conclusion is simple enough. Within the OECD there are just not enough gains from trade in carbon emission rights to generate any major welfare gains from allowing trade. Hence PERMITS generates marginal welfare changes relative to NOTRADE, and also relatively little change in the percentage shares of OECD emissions due to any one region (Table 4).

When trade in carbon emission rights includes non-OECD countries, as in policies LJI and UJI, the gains from trade and the required financial flows are huge. With inelastic oil markets, net purchases of emission rights by the OECD in 2010, for example, are valued at $5 billion under LJI and at a staggering $50 billion under UJI. Offset against these heavy financial flows to non-OECD countries are welfare gains to the OECD of $178 billion and $152 billion, respectively (assuming an inelastic oil market and NOTRADE as the alternative). Whether or not such large financial flows would be politically acceptable or not is a good

Table 4. Burden sharing within the OECD

Present value of compensating payment to equalize burden (1992 $billion)

	A. Elastic oil markets				B. Inelastic oil markets			
	ρ=1		ρ=3		ρ=1		ρ=3	
	NO TRADE	PERMITS TRADE	NO TRADE	PERMITS TRADE	NO TRADE	PERMITS TRADE	NO TRADE	PERMITS TRADE
AUS	0	−36	5	−31	−5	−46	2	−40
CAN	3	6	0	3	16	18	11	14
EU3	−12	−9	−2	0	−18	−14	−5	−2
E_U	106	92	187	162	145	126	254	218
JPN	−81	−53	−65	−38	−131	−90	−110	−71
NZL	1	1	2	3	1	2	4	4
USA	−17	−3	−128	−99	−8	3	−156	−123

C. Base year (1992) carbon emission and GDP statistics for OECD countries

	Base year (1992) carbon emissions in millions of tons				Base year GDP, GDP per capital ($1000) and carbon emissions (grams per $)		
	Oil	Coal	Gas	Total	GDP	GDPPC	C/GDP
AUS	26.5	37.8	7.1	71.3	293.7	14.5	24.3
CAN	61.6	27.2	30.1	118.8	567.0	16.4	21.0
EU3	31.2	11.4	5.0	47.6	523.3	14.0	9.1
E_U	470.8	269.3	135.5	875.6	6932.3	14.7	12.6
JPN	193.2	76.4	30.0	299.6	3563.3	15.1	8.4
NZL	4.5	1.3	2.6	8.4	38.3	11.4	21.8
USA	608.8	470.4	249.1	1328.2	5817.6	17.9	22.8

question, but that is a political marketing issue. This is not aid from the North to the South: the North is simply buying cheaper abatement than they can produce themselves.

It is also apparent that LJI and UJI present two starting points for a fascinating bargaining problem between the OECD and non-OECD. The LJI policy may be viewed as a credible 'threat point' for the OECD, since it does not need the agreement of non-OECD countries to undertake the NOTRADE or PERMITS options. Non-OECD countries generally lose under those policies, so non-OECD countries would be relatively happy to take the deal offered in LJI. Quite plausibly the non-OECD countries would hold out for the deal offered in UJI, but whether or not they are successful is an open bargaining issue. We do not want to speculate here on the outcome of this negotiation, only to point out that there are gains to both groups of countries from a successful negotiation on the precise terms of JI.

It is not at all clear that the 'equitable' outcome described by LJI could be implemented in practice. Table 5 reveals the range of required reductions in emissions by non-OECD countries required to assure no net change in welfare from BAU. While the average is around 25%, there is considerable variation across countries. Sorting out high-cost and low-cost countries would undoubtedly take enormous resources, and would be a matter for considerable controversy.

Table 5. Compensating carbon abatement targets for non-OECD countries under limited JI

	Percentage reduction from BAU under LJI		Base year (1992) carbon emissions in millions on tons				Base year GDP, GDP per capital ($1000) and carbon emissions (grams per $)		
	Elastic oil market	Inelastic oil market	Oil	Coal	Gas	Total	GDP	GDPPc	C/GDP
ARG	5	–	16.0	1.0	9.5	26.4	212.0	4.7	12.5
BRA	15	24	46.6	10.8	1.7	59.1	391.5	3.9	15.1
CHL	24	40	5.7	1.8	0.6	8.2	39.4	4.9	20.7
CHN	25	25	96.0	560.6	7.6	664.2	399.3	1.5	166.3
FSU	45	49	268.3	256.3	285.3	809.9	550.8	7.7	147.0
HKG	15	30	5.6	6.6	0.2	12.4	92.3	16.5	13.5
IDI	27	31	51.2	123.8	6.8	181.7	246.4	1.3	73.7
IDN	29	6	29.9	4.6	8.4	42.9	124.3	2.1	34.5
KOR	19	38	57.0	25.0	3.0	84.9	317.9	7.3	26.7
MEX	30	9	67.4	3.7	12.0	83.1	344.4	6.3	24.1
MYS	45	22	11.8	1.5	6.7	19.9	56.5	5.7	35.3
PHL	19	40	10.5	1.1		11.6	55.5	1.7	20.9
SGP	1	26	8.8			8.8	43.7	12.7	20.2
THA	65	66	18.8	5.1	4.2	28.1	116.4	3.9	24.1
TWN	15	34	22.8	15.6	1.3	39.7	198.0	8.1	20.0
MEA	5	–98	132.1	6.4	55.8	194.4	587.5	6.9	33.1
SSA	12	–13	35.4	79.8	2.5	117.7	311.8	0.4	37.8
RSM	21	–18	55.1	4.6	16.2	75.9	261.7	5.2	29.0
ROW	21	20	210.0	345.8	29.0	584.8	965.6	3.8	60.6

Looking at Table 5, the most sizeable variation occurs in inelastic oil market model, where an *increase* in emissions to double BAU levels are required to compensate MEA (Middle East) for the effects of the carbon tax.

The main qualitative insight from this analysis is that an OECD commitment to undertake some carbon abatement generates substantial 'win–win' alternatives from joint implementation. Set against this comforting result is the need to negotiate a highly differentiated distribution of rights amongst non-OECD countries, not to mention the political specter of large financial flows to non-OECD countries.

Limited JI may be preferred to a global abatement coalition

In scenario GLOBAL all countries agree to the overall abatement target and we allow complete trade in carbon emission rights. However, from Tables 1 and 2 we see that the *distribution of welfare gains under GLOBAL is in many respects inferior for non-OECD countries compared with under UJI.*

The distribution of carbon emissions shown in Table 6 indicates the main reason

Table 6. Value of carbon emission rights exports in 2010 with an elastic oil market ($billions)

	Elastic oil markets				Inelastic oil markets			
	PERMITS	LJI	UJI	GLOBAL	PERMITS	LJI	UJI	GLOBAL
AUS	5	1	–1	0	6	1	–1	0
CAN	1	0	–2	0	2	0	–2	0
EU3	–1	0	–1	0	–1	0	–1	0
E_U	–30	1	–16	–5	–41	–5	–19	–7
JPN	–7	0	–6	–2	–10	–2	–7	–3
NZL	0	0	0	0	0	0	0	0
USA	33	7	–18	–2	45	1	–20	–2
Net OECD	**1**	**9**	**–44**	**–9**	**1**	**–5**	**–50**	**–12**
ARG	0	0	0	0	0	0	0	0
BRA	0	0	0	0	0	–1	0	–1
CHL	0	0	0	0	0	0	0	0
CHN	0	–1	10	2	0	0	12	3
FSU	0	–3	20	11	0	–5	23	13
HKG	0	0	0	0	0	0	0	0
IDI	0	–1	2	0	0	–2	2	0
IDN	0	–1	0	0	0	0	0	0
KOR	0	–1	0	0	0	–2	0	–1
MEX	0	–1	0	0	0	0	0	–1
MYS	0	–1	0	0	0	0	0	0
PHL	0	0	0	0	0	0	0	0
SGP	0	0	0	0	0	0	0	0
THA	0	–1	0	0	0	–1	0	0
TWN	0	0	0	0	0	–1	0	0
MEA	0	1	1	–1	0	14	1	–1
SSA	0	0	1	–1	0	2	1	–1
RSM	0	0	1	0	0	1	1	0
ROW	0	–1	7	1	0	0	8	1

for this result. Many more regions are net importers of emissions rights under GLOBAL, but most significantly the bigger OECD countries do not import as much emissions rights as they did. The reason is simply that it is now more expensive for the producers of these rights to part with them, since *everyone* must undertake abatement. In other words, when it was just the OECD undertaking abatement in LJI or UJI, non-OECD countries could offer emission rights for sale by marginal changes in their production activities. However, under GLOBAL it is as if they have to first meet their own abatement targets and only *then* can they start to offer emission rights for sale. Thus the marginal cost of those rights must be higher, and the demand correspondingly lower.

The gains from trade in carbon are less under GLOBAL compared to JI, due to the commitments to abate that were absent under JI, and so the primary beneficiaries of those rights sales (non-OECD countries) do worse. The OECD does better under GLOBAL, despite the reduced gains from trade in emissions rights, since they are not having to shoulder all of the abatement in order to meet the global target.

Burden sharing across OECD countries is easier with JI

Equalization of burden across OECD countries requires some differentiation of abatement targets (see Table 4), but these differences become small when there are tradeable permit markets and JI. From Table 4 we can compare the NOTRADE columns when we increase the value of ρ, our measure of aversion to inequality, from 1 to 3. There is some noticeable changes in how burdens are allocated, with the USA having much smaller shares and Australia much larger shares, for example. This is due to their relative GDP per capita, shown in column RGDP.

The important implication is that a fair allocation of emission rights across OECD countries is very close to base year emission shares when there is trade within the OECD or JI. Whatever the complexities of burden-sharing vis-à-vis non-OECD countries, there are no major difficulties within the OECD unless we stick to autarky in carbon trade (in scenario NOTRADE).

Why does New Zealand, the poorest of all, not get all of the shares? Simply because it is not big enough to absorb them: as it starts to abate more the costs mount since marginal changes for the USA and E_U are non-marginal changes for little old New Zealand. Hence Australia, despite having a higher GDP per capita than New Zealand, gets the lion's share of the expanded allocations.

Implications

Global warming negotiators would do well to change their focus away from agonizing over diplomatic overtures to lots of countries to join an agreement. It would be better to divert resources into setting up a global system of tradeable carbon permits, ensuring that a number of key OECD countries agree to take joint abatement action, and leave the issue of who should actually undertake the abatement 'to the (global) market' to decide. There are some serious issues involved in setting up markets in global emissions permits, but it does seem feasible (Sandor, 1992). Moreover, several developing countries are already taking unilateral initiatives to lower the transactions costs to JI trades.[14]

An important practical issue in both of the JI scenarios is what reference point is adopted for the negotiated abatement. In our model we know what BAU levels are for non-OECD countries. If JI were implemented in practice, one could anticipate a strong incentive for BAU inflation to set in. Countries that are possible candidates for undertaking JI would have an incentive to overstate their BAU emissions levels, which may just amount to encouraging the use of conservative estimates of energy efficiency and primary energy accounting. In the worst case scenario, we could have strategic incentives akin to the post-military retirement plan of Major Major in Catch-22, who was going to return to the United States to be paid *not* to grow corn.

Although this is not an issue in the formal sense for our simulations, it can be dealt with conceptually by redefining the deal that the OECD is viewed as offering to JI countries. Let the proffered contract now include a specification of what the OECD regards as the BAU profile of the JI country, even if it is wrong. If it exceeds the actual BAU profile of the JI country, which is presumably known only to the JI country, then the JI country is being asked and paid to produce less abatement than it actually has to; otherwise it is being asked and paid to produce more abatement than it would have to if the true BAU profile were used. In each case the only point is that the JI country is being offered a higher or lower *price* for it's abatement than needed in some full-information setting. In neither case does it have to accept the contract, although one could anticipate substantial inefficiencies emerging if prices are too far from their full-information values.[15] Hence uncertainty about BAU levels can be just thought of as something that the parties to a potential JI transaction need to contract around, hardly a new phenomenon.

There is nothing to stop the OECD revising its estimate of the BAU profile of potential JI countries. Indeed, it will have to do this in the face of changes in fundamentals if it is to be able to endogenously change its own emissions target to ensure the global target. So these changes in OECD-estimated BAU profiles will become part of the JI contracting game if fundamentals change, as one would expect over such a long time horizon.

The possibility of changes in fundamentals also raises the issue of important advantages of tradeable emission rights over JI. If technology changes such that some country that is contracted to undertake JI is no longer the lowest marginal cost abater, it would be efficient for it to be able to contract with the cheaper country to assume it's obligation. This is trivial under tradeable permits, but formally impossible under JI. In our model the distinction is irrelevant, since there are no changes in fundamentals as posited. But it would be important to keep this in mind in practice, allowing short-term JI contracts to form the basis of possible markets in tradeable permits (most formal spot and futures markets in fact emerged slowly from the shadows of bilateral, grey transactions in this way).

In any event, these issues of asymmetric information and strategic definition of reference points for defining JI abatement are not germane to our simulations. In our simulations all parties are assumed to behave as if they have full information about the true BAU profiles.[16]

Our approach flies directly in the face of those who would argue that the only equitable thing to do is for each country to reduce it's domestic emissions. This view is often put on purely moral grounds, so as to avoid the uncomfortable light of logic. The overall environmental goal is to reduce *global* emissions. It is a wholly separate matter to then argue that the best way to achieve the goal is to inflict pain equally on each country, however one wants to define 'pain'.[17] That step entails value judgements which we firmly reject, even if we accept the overall global environmental goal. Moreover, equity concerns can still play a role in designing an attractive distribution of the burdens of abating global warming. We demonstrate how varying degrees of aversion to inequality influence the allocations of emission rights within the OECD necessary to attain given global abatement targets. However, we conclude that those considerations appear to be second-order once the efficiency gains from joint implementation and tradeable permits are recognized.

Finally, the implications of our results for ongoing negotiations are serious. The OECD appears set to undertake abatement because of blunt political motives. There is little that the rest of the world can do about this, hence the parallel with the structure of the Uruguay Round negotiations is quite striking (Harrison *et al.*, 1997).[18] Talk is cheap, and tends to be ignored in international negotiations when substance replaces rhetoric. The real issue to be decided is what role the non-OECD countries will play in implementing this agreement. If the Uruguay Round experience is representative of the negotiating process, it strikes us as unlikely that the non-OECD countries will be able to act as a coherent coalition, due to the heterogeneity of their economies and geo-political connections.

On the other hand, the OECD has a clear vested interest in allowing itself to pay the non-OECD countries to undertake abatement for it. Despite the huge financial flows involved, it is cost-effective for the OECD to allow JI and/or tradeable emissions. If it does so, there is *considerably less need for tailoring emissions allocations to national circumstances*. Hence our major conclusion is that attention should be diverted away from burden sharing concerns[19] and towards changes in the draft negotiating instrument that will allow joint implementation and/or trade in emission rights amongst all countries, not just signatories.

Notes

1. This should not be confused with diplomatic notions of 'activities implemented jointly', which is a very different beast. The United Nations Framework Convention (1995) allows these experimental projects, but any emissions

reductions do not apply to national commitments, diminishing the immediate incentive for any OECD countries to undertake them. There are also other requirements, such as their being funded in addition to official development assistance, but these are not operationally meaningful.

2. The original IIAM model consisted of a five region model of trade, investment and fossil fuel markets together with open-economy models for 80 separate countries. In the present study we have extended the IIAM multi-regional component (MRT) to include 25 countries and regions which together account for global economic activity.
3. These are: AUS Australia; NZL New Zealand; JPN Japan; KOR Republic of Korea; IDN Indonesia; MYS Malaysia; PHL Philippines; SGP Singapore; THA Thailand; CHN China; HKG Hong Kong; TWN Taiwan; IDI India; CAN Canada; USA United States of America MEX Mexico; ARG Argentina; BRA Brazil; CHL Chile; RSM Rest of South America; E_U European Union 12; EU3 Austria, Finland and Sweden; FSU Former Soviet Union; MEA Middle East and North Africa; SSA Sub Saharan Africa; ROW Rest of World. The OECD consists of AUS, NZL, JPN, CAN, USA, E_U and EU3 in this model.
4. This formulation offers significant empirical advantages vis-a-vis a standard Armington model. First, in this framework it is not necessary to collect a full matrix of bilateral trade flows. Second, there are some appealing properties of the theoretical framework, such as the optimal tariff for any small nation being zero.
5. The model does not formally distinguish between crude and refined oil. In the model specification, oil production levels are calibrated to DOE/IEA statistics for crude, and oil demand quantities are consistent with DOE/IEA statistics for refined oil products.
6. That is, the elasticity of substitution between domestic composite goods and imported composite goods is one half of the elasticity of substitution between alternate import sources. The former elasticity is set to 4 in our default specification, and the intra-import elasticity is equal to 8. The elasticity of transformation between goods produced for the domestic and export markets is 2.
7. For example, some environmentalists would be willing to pay more to ensure that their own country undertook abatement. Whatever the logic of the ethical motives underlying this possibility, if it means that they would actually be willing to pay more then that would violate our assumption.
8. But not in our model.
9. The cutback scenario we consider does not halt the rise in carbon emissions through 2030. In fact, this reduction is quite modest compared with targets such as the AOSIS protocol which have been proposed; see Wigley, Richels and Edmonds (1996) for a discussion of the timing issue. We have chosen this scenario in order to look at the economic implications of a policy which currently seems plausible at this point in the negotiating process.

10. It would be a simple matter to extend the analysis to examine smaller or larger coalitions.
11. Efficiency is always relative to some baseline, and here it is naturally relative to NOTRADE. It is unlikely to be efficient to have OECD countries abate relative to a situation in which any of the non-OECD countries can abate.
12. Specifically, we assume oil supply elasticities of 8 and 0.5, respectively.
13. Disaggregating the non-energy good into more goods would probably mitigate the welfare impacts we obtain. The reason is that our approach implicitly assumes that these goods are produced in a fixed-coefficient fashion to form one composite good. This implies that we likely understate the ability of substitution to mitigate the effects of these terms of trade changes.
14. The best-known examples are in Costa Rica, which is working hard to establish itself as the market leader amongst developing countries in this area. Under 'Costa Rica's Certified Transferable Offset (CFO) programme a national Carbon Fund will sell CTOs (units of greenhouse gas emissions reduced or sequestered in bilaterally approved projects) to investors and provide financial resources to project developers, while a National Forestry Financing Fund will administer and finance national joint implementation land-use projects. Instead of having to carry out investment feasibility analyses, the investor simply buys offset certificates, so transaction costs are low. Investor risk is lowered, too, since these offsets come from diverse projects. As innovative as this mechanism looks, it is still too early to know whether it will attract enough investors willing to speculate exclusively on the future value of the credits obtained. The Norwegian Government is currently considering buying $2 million of CTOs. Since this would fall under its joint implementation pilot programme, Norway would not seek credits. Even so, such a deal could attract other investors (Zollinger and Dower, 1996).
15. One has to be very careful when using terms like 'inefficiency' in such asymmetric information settings. Implicitly we are defining it relative to the efficient allocation in a full-information world, but if that world does not exist then one should not use that fictional reference point. Our goal here is to just to raise these issues for further study.
16. It would be possible to evaluate the effects of the informational asymmetry just discussed using an extension of our CGE model. One could solve the model in the year 2000 assuming that fundamentals will not change from their BAU path, then shock the model in 2005 (or some later year) parametrically with random changes in fundamentals such as elasticities and endowments, then see if there is a need for any changes in policies. The only complication would be undertaking welfare evaluation. It would then be possible to examine alternative mechanisms for having non-OECD countries reveal information about this change in fundamentals.
17. We conjecture that the ambiguities in defining this word have been more than enough fuel for a burgeoning literature, leading many to ignore the inefficiency of this policy approach.

18. In those negotiations the major items of agreement on agriculture, textiles, and manufactured tariff reform did not require the agreement of more than a handful of countries. Indeed, reform of the agricultural subsidy war between the US and EU was effectively the result of bilateral negotiations, and the elimination of the Multi-Fibre Arrangement could have been done unilaterally in Washington and Brussels by just tearing up some pieces of paper (quotas).
19. Burden sharing can still be important, such as deciding how to meet EU-wide commitments within the member states of the EU or if JI *and* tradeable permits are not allowed.

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Appendix A: input data

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$TITLE A 25 Region Energy-Economy Dataset
SET R Regions /
        AUS     Australia
        NZL     New Zealand
        JPN     Japan
        KOR     Republic of Korea
        IDN     Indonesia
        MYS     Malaysia
        PHL     Philippines
        SGP     Singapore
        THA     Thailand
        CHN     China
        HKG     Hong Kong
        TWN     Taiwan
        IDI     India
        CAN     Canada
        USA     United States of America
        MEX     Mexico
        ARG     Argentina
        BRA     Brazil
        CHL     Chile
        RSM     Rest of South America
        E_U     European Union 12
        EU3     Austria Finland and Sweden
        FSU     Former Soviet Union
        MEA     Middle East and North Africa
        SSA     Sub Saharan Africa
        ROW     Rest of World/;

SET OECD(R) Member countries of the OECD /
        AUS     Australia
        NZL     New Zealand
        JPN     Japan
        CAN     Canada
        USA     United States of America
        E_U     European Union 12
        EU3     Austria Finland and Sweden /;

SET MAP5 (R,R5) Assignment of regions into trade zones /
        AUS.OECD     Australia
        NZL.OECD     New Zealand
        JPN.OECD     Japan
        KOR.ASIA     Republic of Korea
        IDN.ASIA     Indonesia
        MYS.ASIA     Malaysia
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PHL.ASIA	Philippines
SGP.ASIA	Singapore
THA.ASIA	Thailand
CHN.ASIA	China
HKG.ASIA	Hong Kong
TWN.ASIA	Taiwan
IDI.ASIA	India
CAN.OECD	Canada
USA.OECD	United States of America
MEX.OTHR	Mexico
ARG.OTHR	Argentina
BRA.OTHR	Brazil
CHL.OTHR	Chile
RSM.OTHR	Rest of South America
E_U OECD	European Union 12
EU3.OECD	Austria Finland and Sweden
FSU.CPEE	Former Soviet Union
MEA.MIDE	Middle East and North Africa
SSA.OTHR	Sub Saharan Africa
ROW.OTHR	Rest of World

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TABLE MACRO (R,*) Benchmark macroeconomic statistics

* RGDPC is real GDP per capita (from the Penn World Tables)

*	EXPORT $billions	GDP $billion	LVSHR share	RGDPC $1985	
AUS	39.632	293.723	0.620	14458	
NZL	11.571	38.344	0.585	11363	
JPN	365.077	3563.344	0.593	15105	
KOR	80.992	317.873	0.507	7251	
IDN	26.136	124.348	0.319	2102	
MYS	36.161	56.490	0.312	5746	
PHL	14.328	55.545	0.420	1689	
SGP	62.431	43.743	0.525	12653	
THA	37.531	116.416	0.219	3942	
CHN	93.602	399.307	0.544	1493	
HKG	42.608	92.255	0.484	16471	
TWN	90.157	197.958	0.605	8063	
IDI	22.888	246.439	0.463	1282	
CAN	128.977	566.986	0.586	16362	
USA	564.548	5817.560	0.663	17945	
MEX	48.053	344.422	0.305	6253	
ARG	13.295	212.034	0.472	4706	
BRA	38.225	391.461	0.438	3882	
CHL	12.619	39.448	0.360	4890	
RSM	50.517	261.708	0.338	5185	! Uruguay
E_U	746.943	6932.258	0.584	14700	! West Germany
EU3	163.183	523.342	0.603	13986	! Sweden
FSU	29.320	550.837	0.567	7741	! U.S.S.R. (1989)
MEA	60.558	587.475	0.478	6885	! Saudi Arabia (1989)
SSA	39.555	311.761	0.455	424	! Zaire (1989)
ROW	228.467	965.593	0.546	3807;	! Turkey

TABLE ENERGY (FF ,*,*) Base year energy flows (exajoules)

	INDUSTRY	FINAL	OUTPUT	EXPORT
OIL.AUS	0.364	0.961	1.038	–0.287
OIL.NZL	0.074	0.151	0.098	–0.127
OIL.JPN	5.362	4.299	0.230	–9.431
OIL.KOR	1.601	1.247	0.007	–2.842
OIL.IDN	0.615	0.881	2.966	1.470
OIL.MYS	0.292	0.298	1.268	0.678
OIL.PHL	0.281	0.246	0.017	–0.510
OIL.SGP	0.285	0.157	0.037	–0.405
OIL.THA	0.361	0.579	0.099	–0.841
OIL.CHN	3.200	1.599	5.357	0.558
OIL.HKG	0.123	0.158		–0.281
OIL.TWN	0.703	0.436	0.023	–1.116
OIL.IDI	0.860	1.699	0.976	–1.584
OIL.CAN	0.957	2.122	4.078	0.998
OIL.USA	4.883	25.557	16.435	–14.005
OIL.MEX	1.422	1.947	5.660	2.291
OIL.ARG	0.207	0.591	1.154	0.357
OIL.BRA	0.943	1.387	1.291	–1.039
OIL.CHL	0.093	0.192	0.019	–0.266
OIL.RSM	0.943	1.814	7.158	4.401
OIL.E_U	9.946	13.593	6.058	–17.480
OIL.EU3	0.499	1.060	0.176	–1.384
OIL.FSU	12.287	1.126	17.220	3.807
OIL.MEA	3.200	3.404	38.247	31.643
OIL.SSA	1.011	0.761	6.293	4.521
OIL.ROW	6.624	3.876	11.375	0.874
OIL.WORLD	57.136	70.143	127.278	
COL.AUS	1.506	0.004	4.842	3.332
COL.NZL	0.050	0.001	0.073	0.022
COL.JPN	3.044	0.011	0.091	–2.964
COL.KOR	0.752	0.246	0.178	–0.820
COL.IDN	0.184		0.583	0.399
COL.MYS	0.059		0.005	–0.054
COL.PHL	0.043		0.025	–0.018
COL.THA	0.203		0.188	–0.015
COL.CHN	17.061	5.363	22.923	0.498
COL.HKG	0.263			–0.263
COL.TWN	0.623		0.017	–0.606
COL.IDI	4.867	0.084	4.775	–0.175
COL.CAN	1.086	0.002	1.513	0.424
COL.USA	18.444	0.371	21.320	2.505
COL.MEX	0.149		0.126	–0.023
COL.ARG	0.039		0.009	–0.031
COL.BRA	0.432		0.086	–0.346
COL.CHL	0.073	0.001	0.049	–0.025
COL.RSM	0.181	0.001	0.661	0.479
COL.E_U	10.305	0.467	6.693	–4.080
COL.EU3	0.431	0.026	0.104	–0.353
COL.FSU	4.258	5.993	10.696	0.444
COL.MEA	0.244	0.014	0.034	–0.225
COL.SSA	2.847	0.346	4.592	1.398
COL.ROW	9.892	3.941	14.330	0.497
COL.WORLD	77.039	16.873	93.912	
GAS.AUS	0.408	0.096	0.712	0.207
GAS.NZL	0.179	0.006	0.181	–0.004

	INDUSTRY	FINAL	OUTPUT	EXPORT
GAS.JPN	1.786	0.359	0.229	-1.916
GAS.KOR	0.142	0.073	0.028	-0.187
GAS.IDN	0.587	0.014	1.754	1.153
GAS.MYS	0.475	0.001	0.806	0.329
GAS.THA	0.301		0.295	-0.006
GAS.CHN	0.531	0.014	0.533	-0.011
GAS.HKG	0.005	0.011	0.016	
GAS.TWN	0.070	0.023	0.035	-0.059
GAS.IDI	0.479	0.006	0.540	0.054
GAS.CAN	1.078	1.069	4.078	1.930
GAS.USA	12.596	5.194	16.305	-1.485
GAS.MEX	0.812	0.042	0.737	-0.116
GAS.ARG	0.490	0.189	0.597	-0.082
GAS.BRA	0.115	0.006	0.118	-0.002
GAS.CHL	0.036	0.009	0.044	
GAS.RSM	1.112	0.044	1.287	0.131
GAS.E_U	6.099	3.583	5.592	-4.089
GAS.EU3	0.285	0.072	0.044	-0.313
GAS.FSU	16.970	3.411	22.784	2.403
GAS.MEA	3.817	0.172	5.654	1.665
GAS.SSA	0.139	0.038	0.175	-0.002
GAS.ROW	1.855	0.214	2.470	0.400
GAS.WORLD	50.367	14.647	65.014;	

Table GROW Annual growth rates (%)

	2000	2005	2010	2015	2020	2025	2030
AUS	2.3	2.2	2.1	2.0	1.9	1.8	1.7
NZL	2.3	2.2	2.1	2.0	1.9	1.8	1.7
JPN	2.3	2.2	2.1	2.0	1.9	1.8	1.7
KOR	6.0	5.5	5.0	4.5	4.5	4.5	4.5
IDN	6.0	5.5	5.0	4.5	4.5	4.5	4.5
MYS	6.0	5.5	5.0	4.5	4.5	4.5	4.5
PHL	6.0	5.5	5.0	4.5	4.5	4.5	4.5
SGP	6.0	5.5	5.0	4.5	4.5	4.5	4.5
THA	6.0	5.5	5.0	4.5	4.5	4.5	4.5
CHN	6.0	5.5	5.0	4.5	4.5	4.5	4.5
HKG	6.0	5.5	5.0	4.5	4.5	4.5	4.5
TWN	6.0	5.5	5.0	4.5	4.5	4.5	4.5
IDI	6.0	5.5	5.0	4.5	4.5	4.5	4.5
CAN	2.3	2.2	2.1	2.0	1.9	1.8	1.7
USA	2.3	2.2	2.1	2.0	1.9	1.8	1.7
MEX	4.0	4.0	4.0	4.0	4.0	4.0	4.0
ARG	4.0	4.0	4.0	4.0	4.0	4.0	4.0
BRA	4.0	4.0	4.0	4.0	4.0	4.0	4.0
CHL	4.0	4.0	4.0	4.0	4.0	4.0	4.0
RSM	4.0	4.0	4.0	4.0	4.0	4.0	4.0
E_U	2.3	2.2	2.1	2.0	1.9	1.8	1.7
EU3	2.3	2.2	2.1	2.0	1.9	1.8	1.7
FSU	4.0	0.0	4.0	3.5	3.0	3.0	3.0
MEA	4.0	4.0	4.0	4.0	4.0	4.0	4.0
SSA	4.0	4.0	4.0	4.0	4.0	4.0	4.0
ROW	4.0	4.0	4.0	4.0	4.0	4.0	4.0 ;

Table EPRICE (FF,*,*) Base year energy prices ($ per GJ)

	INDUSTRY	FINAL	PRODUCER
OIL.WORLD			3.500
COL.WORLD			2.100
GAS.WORLD			2.900
OIL.AUS	6.166	8.324	5.138
OIL.NZL	5.630	7.600	4.691
OIL.JPN	6.791	9.169	5.660
OIL.KOR	5.451	7.359	4.543
OIL.IDN	4.200	5.670	3.500
OIL.MYS	5.451	7.359	3.5
OIL.PHL	5.451	7.359	4.543
OIL.SGP	5.451	7.359	4.543
OIL.THA	5.451	7.359	4.543
OIL.CHN	4.200	5.670	3.500
OIL.HKG	5.451	7.359	4.543
OIL.TWN	5.451	7.359	4.543
OIL.IDI	4.200	5.670	3.500
OIL.CAN	3.500	5.911	3.500
OIL.USA	4.200	5.670	3.500
OIL.MEX	4.647	6.273	3.500
OIL.ARG	4.200	5.670	3.500
OIL.BRA	5.451	7.359	4.543
OIL.CHL	4.200	5.670	3.500
OIL.RSM	4.200	5.670	3.500
OIL.E_U	7.774	10.496	6.479
OIL.EU3	5.451	7.359	4.543
OIL.FSU	0.626	0.844	0.521
OIL.MEA	4.200	5.670	3.500
OIL.SSA	5.451	7.359	3.500
OIL.ROW	4.200	5.670	3.500
COL.AUS	1.000	1.000	1.000
COL.NZL	1.900	1.900	1.900
COL.JPN	3.600	3.600	3.600
COL.KOR	3.500	3.500	3.500
COL.IDN	1.400	1.400	1.400
COL.MYS	3.500	3.500	3.500
COL.PHL	3.500	3.500	3.500
COL.SGP	3.500	3.500	3.500
COL.THA	3.500	3.500	3.500
COL.CHN	1.400	1.400	1.400
COL.HKG	3.500	3.500	3.500
COL.TWN	3.500	3.500	3.500
COL.IDI	2.100	2.100	2.100
COL.CAN	1.900	1.900	1.900
COL.USA	1.400	1.400	1.400
COL.MEX	2.100	2.100	2.100
COL.ARG	2.100	2.100	2.100
COL.BRA	3.500	3.500	3.500
COL.CHL	2.100	2.100	2.100
COL.RSM	1.400	1.400	1.400
COL.E_U	3.300	3.300	3.300
COL.EU3	3.500	3.500	3.500
COL.FSU	0.700	0.700	0.700
COL.MEA	2.100	2.100	2.100
COL.SSA	3.500	3.500	2.100
COL.ROW	1.400	1.400	1.400

	INDUSRY	FINAL	PRODUCER
GAS-AUS	3.400	3.400	2.900
GAS.NZL	7.300	7.300	7.300
GAS.JPN	11.900	11.900	11.900
GAS.KOR	8.400	8.400	8.400
GAS.IDN	2.800	2.800	2.800
GAS.MYS	8.400	8.400	2.900
GAS.PHL	8.400	8.400	8.400
GAS.SGP	8.400	8.400	8.400
GAS.THA	8.400	8.400	8.400
GAS.CHN	2.900	2.900	2.900
GAS.HKG	8.400	8.400	8.400
GAS.TWN	8.400	8.400	8.400
GAS.IDI	2.800	2.800	2.800
GAS.CAN	2.200	2.200	2.200
GAS.USA	2.900	2.900	2.900
GAS.MEX	2.900	2.900	2.900
GAS.ARG	2.900	2.900	2.900
GAS.BRA	8.400	8.400	8.400
GAS.CHL	2.900	2.900	2.900
GAS.RSM	2.800	2.800	2.800
GAS.E_U	4.300	4.300	4.300
GAS.EU3	8.400	8.400	8.400
GAS.FSU	0.500	0.500	0.500
GAS.MEA	2.800	2.800	2.800
GAS.SSA	8.400	8.400	8.400
GAS.ROW	2.800	2.800	2.800;

Table IMPORTS (R,R5) Benchmark imports (1992 $billions)

	OECD	ASIA	CPEE	MIDE	OTHR
AUS	36.239	9.044	0.061	0.688	2.228
NZL	8.366	1.429	0.014	0.104	0.483
JPN	130.400	73.377	3.077	6.896	29.946
KOR	55.859	9.409	0.578	0.833	4.896
IDN	21.058	6.241	0.051	0.401	1.551
MYS	23.759	12.376	0.078	0.174	1.498
PHL	10.601	3.743	0.090	0.220	0.953
SGP	38.422	24.029	0.133	0.565	3.212
THA	27.727	9.420	0.313	0.465	3.349
CHN	52.183	27.367	3.573	0.669	5.847
HKG	24.889	27.875	0.135	1.081	3.236
TWN	58.541	13.425	0.031	0.276	3.703
IDI	13.822	2.467	0.285	1.521	2.104
CAN	118.294	8.124	0.222	0.353	4.669
USA	346.659	110.546	1.208	7.096	78.432
MEX	62.401	1.821	0.026	0.107	3.263
ARG	11.053	1.509	0.041	0.107	6.029
BRA	18.645	1.039	0.256	0.801	5.234
CHL	6.851	1.059	0.075	0.075	2.585
RSM	58.025	7.345	0.200	0.622	15.958
E_U	338.367	95.384	10.566	26.345	180.815
EU3	120.981	6.745	1.536	1.162	17.116
FSU	36.785	5.318	2.959	0.401	4.991
MEA	151.181	18.773	0.344	6.103	18.777
SSA	53.149	8.056	0.059	0.663	8.128
ROW	195.675	20.912	3.409	2.830	21.726;

TABLE FFPROD Fossil fuel production projections from DOE and IEA (exajoules)

	2000	2005	2010	2015	2020	2025	2030
OIL.AUS	1.048	1.013	1.008	1.003	1.002	1.001	1.009
OIL.NZL	0.098	0.095	0.095	0.094	0.094	0.094	0.095
OIL.JPN	0.232	0.225	0.223	0.222	0.222	0.222	0.224
OIL.KOR	0.008	0.008	0.008	0.008	0.008	0.008	0.008
OIL.IDN	3.302	3.467	3.535	3.525	3.541	3.582	3.647
OIL.MYS	1.412	1.482	1.511	1.507	1.514	1.532	1.559
OIL.PHL	0.019	0.020	0.020	0.020	0.020	0.021	0.021
OIL.SGP	0.041	0.043	0.044	0.044	0.044	0.045	0.046
OIL.THA	0.110	0.116	0.118	0.117	0.118	0.119	0.122
OIL.CHN	5.965	6.263	6.385	6.368	6.397	6.471	6.588
OIL.TWN	0.025	0.027	0.027	0.027	0.027	0.028	0.028
OIL.IDI	1.087	1.141	1.163	1.160	1.165	1.179	1.200
OIL.CAN	4.118	3.980	3.957	3.939	3.934	3.943	3.965
OIL.USA	16.595	16.040	15.947	15.874	15.857	15.891	15.978
OIL.MEX	6.758	7.141	7.347	7.338	7.432	7.622	7.901
OIL.ARG	1.378	1.456	1.498	1.496	1.516	1.554	1.611
OIL.BRA	1.541	1.629	1.676	1.674	1.695	1.738	1.802
OIL.CHL	0.023	0.024	0.025	0.025	0.025	0.026	0.027
OIL.RSM	8.546	9.032	9.291	9.281	9.400	9.639	9.993
OIL.E_U	6.117	5.913	5.878	5.852	5.845	5.858	5.890
OIL.EU3	0.178	0.172	0.171	0.170	0.170	0.170	0.171
OIL.FSU	13.158	15.180	17.238	19.301	21.611	24.197	27.093
OIL.MEA	47.039	54.345	60.107	64.798	70.001	75.758	82.120
OIL.SSA	7.513	7.940	8.168	8.159	8.262	8.474	8.785
OIL.ROW	13.581	14.352	14.764	14.748	14.937	15.317	15.879
COL.AUS	4.601	4.706	4.896	5.148	5.424	5.726	6.054
COL.NZL	0.069	0.071	0.074	0.078	0.082	0.086	0.091
COL.JPN	0.086	0.088	0.092	0.097	0.102	0.108	0.114
COL.KOR	0.237	0.278	0.314	0.351	0.394	0.443	0.499
COL.IDN	0.774	0.909	1.026	1.149	1.289	1.450	1.635
COL.MYS	0.006	0.008	0.009	0.010	0.011	0.012	0.014
COL.PHL	0.033	0.039	0.044	0.049	0.055	0.062	0.070
COL.THA	0.250	0.294	0.332	0.371	0.416	0.468	0.528
COL.CHN	30.453	35.751	40.381	45.193	50.711	57.042	64.308
COL.TWN	0.023	0.027	0.031	0.034	0.038	0.043	0.049
COL.IDI	6.344	7.447	8.412	9.414	10.564	11.883	13.396
COL.CAN	1.437	1.470	1.529	1.608	1.694	1.789	1.891
COL.USA	20.256	20.719	21.556	22.663	23.881	25.210	26.654
COL.MEX	0.126	0.134	0.136	0.137	0.138	0.141	0.145
COL.ARG	0.009	0.009	0.009	0.009	0.009	0.010	0.010
COL.BRA	0.085	0.091	0.092	0.092	0.094	0.095	0.098
COL.CHL	0.049	0.052	0.053	0.053	0.054	0.055	0.056
COL.RSM	0.661	0.702	0.709	0.714	0.723	0.737	0.756
COL.E_U	6.359	6.504	6.767	7.115	7.497	7.914	8.367
COL.EU3	0.099	0.101	0.105	0.111	0.117	0.123	0.130
COL.FSU	8.776	8.733	8.719	8.715	8.709	8.705	8.701
COL.MEA	0.032	0.032	0.032	0.032	0.032	0.032	0.032
COL.SSA	4.589	4.876	4.927	4.959	5.024	5.121	5.252
COL.ROW	14.320	15.216	15.375	15.476	15.680	15.981	16.389
GAS.AUS	0.800	0.850	0.898	0.953	1.013	1.077	1.147
GAS.NZL	0.204	0.217	0.229	0.243	0.258	0.275	0.292
GAS.JPN	0.257	0.274	0.289	0.307	0.326	0.347	0.369
GAS.KOR	0.038	0.047	0.059	0.072	0.089	0.109	0.133
GAS.IDN	2.420	3.014	3.745	4.612	5.663	6.942	8.494
GAS.MYS	1.113	1.386	1.721	2.120	2.603	3.191	3.905

GAS.THA	0.407	0.507	0.630	0.776	0.952	1.167	1.438
GAS.CHN	0.736	0.917	1.139	1.403	1.723	2.112	2.584
GAS.HKG	0.022	0.028	0.034	0.042	0.052	0.064	0.078
GAS.TWN	0.048	0.060	0.074	0.091	0.112	0.137	0.168
GAS.IDI	0.745	0.928	1.153	1.421	1.744	2.138	2.616
GAS.CAN	4.583	4.871	5.145	5.461	5.804	6.174	6.572
GAS.USA	18.324	19.476	20.573	21.835	23.207	24.688	26.279
GAS.MEX	0.870	1.076	1.330	1.632	1.995	2.466	3.022
GAS.ARG	0.705	0.871	1.077	1.322	1.616	1.997	2.448
GAS.BRA	0.139	0.172	0.213	0.261	0.320	0.395	0.484
GAS.CHL	0.052	0.064	0.079	0.097	0.119	0.147	0.180
GAS.RSM	1.519	1.878	2.321	2.849	3.482	4.305	5.275
GAS.E_U	6.285	6.680	7.056	7.489	7.959	8.467	9.013
GAS.EU3	0.049	0.052	0.055	0.059	0.062	0.066	0.071
GAS.FSU	25.486	27.328	28.173	28.480	28.864	29.248	29.631
GAS.MEA	7.790	8.755	10.165	11.649	13.429	15.507	17.881
GAS.SSA	0.207	0.255	0.316	0.387	0.473	0.585	0.717
GAS.ROW	2.916	3.604	4.454	5.467	6.681	8.261	10.123;

Appendix B: an algebraic formulation

Production

Aggregate output in region *r* describes the supply of non-energy goods to the domestic and export markets. These technologies exhibit constant returns to scale, and production takes place under perfect competition. The unit production function for region *r* is a nested constant-elasticity-of-substitution aggregate:

$$Y_{rt} = \left\{ \beta \left(\phi_{rt} \frac{E_{rt}}{\overline{E}_r} \right)^{\rho} + (1-\beta) \left[\left(\frac{L_{rt}}{\overline{L}_r} \right)^{\alpha} \left(\frac{K_{rt}}{\overline{K}_r} \right)^{1-\alpha} \right]^{\rho} \right\}^{1/\rho}$$

in which E_{rt} is the composite input of fossil fuels, L represents labor supply, and K_{rt} is the capital stock. The term ϕ_{rt} is an exogenous energy efficiency improvement index which measures changes in technical efficiency over time.

Energy inputs to the macro production function are in turn a nested CES aggregation of oil, gas and coal in which oil and gas are modeled as relatively close substitutes. Both oil and gas substitute with coal at a lower rate.

The allocation of non-energy production between domestic and export markets is characterized by a constant elasticity of transformation aggregation:

$$Y_{rt} = \left\{ \delta \left(\frac{D_{rt}}{\overline{D}_r} \right)^{\eta} + (1-\delta) \left(\frac{X_{rt}}{\overline{X}_r} \right)^{\eta} \right\}^{1/\eta}$$

In equilibrium there is a period-by-period balance between exports from regions in each export zone (z) and global demand for those goods:

$$\sum_{r \in z} X_{rt} = \sum_{r} M_{zrt} \qquad \forall z$$

Non-energy trade

Each of the 25 countries and regions is assigned to one of five export zones. We presume that non-energy inputs are distinguished solely by export zone and not by country of origin. The aggregation of domestic and imported goods then is characterized by a nested Armington index:

$$A_{rt} = \left[\theta_D \left(\frac{D_{rt}}{\overline{D}_r} \right)^{\rho_{DM}} + (1-\theta_D) \left[\sum_z \alpha_{zr} \left(\frac{M_{zrt}}{\overline{M}_{zr}} \right)^{\rho_{MM}} \right]^{\rho_{DM}/\rho_{MM}} \right]^{1/\rho_{DM}}$$

Elasticity parameters and relative prices determine the cost-minimizing composition of non-energy demand in region r.

International energy markets

The model incorporates international markets for oil, coal and natural gas. For each of these fuels, we have a global market clearing condition:

$$\sum_r X_{rt}^f = \sum_r M_{rt}^f \qquad \forall t, f \in \{oil, coal, gas\}$$

Trade costs for gas and coal (and tariffs for oil) drive a wedge between domestic and international prices for fuels. In equilibrium the following inequalities relate domestic and international market prices:

$$p_{wt}^f (1 - tx_{rt}^f) + \tau_{fr}^X \le p_{rt}^f \le p_{wt}^f (1 + tm_{rt}^f) + \tau_{fr}^M$$

in which t denotes an export or import tax, and τ denotes a transport cost in nominal terms. These wedges are calibrated to base year prices and trade flows. In the calibration, differences between domestic and international oil prices are attributed to taxes, and differences between domestic and international coal and gas prices are attributed to transport costs.

Consumer choice

Final demand in each region is characterized by a representative agent who allocates income to purchase composite consumption goods in each period of the model in order to maximize utility:

$$U_r = \left(\sum_{t=2000}^{2030} \delta_{rt} \, C_{rt}^{\rho} \right)^{1/\rho}$$

In this equation parameter ρ characterizes the intertemporal elasticity of substitution:

$$\sigma_T = \frac{1}{(1-\rho)}$$

The term δ_{rt} represents the discounting of future consumption. Consumers choose demands in each period to maximize the present value of consumption over the model horizon:

$$\begin{aligned} &\max U_r(C_{rt}) \\ &s.t. \\ \sum_t C_{rt}\, p_{rt} &= \sum_t w_t \, \bar{L}_t + p_{r0}^K K_0 + \sum_{f,t} p_{rt}^f \, \bar{R}_{rt}^f \\ &+ \sum_t T_t - p_{rT+1}^K K_{T+1} \end{aligned}$$

in which the budget constraint equates the present value of consumption demand to the present value of wage income, the value of the initial capital stock, the present value of rents on fossil energy production, tariff revenues, less the value of post-terminal capital.

In order to do welfare analysis we need to account for the impact of policies during the time horizon of the model on consumption during the post-terminal period. We begin with the assumption that the model is sufficiently close to a steady-state equilibrium at the end of the model horizon that we may approximate post-terminal consumption assuming that the steady-state relationships apply, namely:

$$C_{t+1} = C_t(1+g) \quad \forall t > T$$

Given this assumption, we may then construct infinite horizon welfare based on the equilibrium computed over the endogenous years:

$$W_r = U_r + \sum_{t=2035} \delta_{rt} C_{rt} = U_r + C_{2030} \sum_{t=2035}^{\infty} \delta_{rt} (1+g_{rT})^{t-2030}$$

Assuming constancy of the discount rate and consumption growth rate, we may then approximate the infinite horizon welfare as:

$$W_r = U_r + \Gamma_r(\delta, g_{rT})\, C_{2030}$$

Investment and capital accumulation

Physical capital stocks depreciate at a constant geometric rate, and they are incremented by investment from domestic output. With five year time periods and a two-year gestation lag for capital formation, we assume that one unit of investment in year t produces three units of capital in period t+1 and two units in period t. The transition equation for capital stock is:

$$K_{rt+5} = \lambda_r K_{rt} + 2 I_{rt} + 3 I_{rt-5}$$

The finite horizon poses some problems with respect to capital accumulation. In the absence of any terminal adjustment, the capital stock in the model would have no value after 2030, and this would have significant repercussions for rates of investment in the periods leading up to the end of the model horizon. In order to correct for these effects, we apply an auxiliary equation which constrains terminal investment to increase in proportion to final demand:

$$\frac{I_{rT}}{I_{rT-1}} = \frac{C_{rT}}{C_{rT-1}}$$

It should be emphasized that we apply this side constraint along with the other economic equilibrium conditions (zero profit, market clearance and income balance), but the application of the constraint has no implications for the investment and consumption activities because these impacts do not enter into the zero profit conditions for these activities. Instead, we close the model by including a terminal capital stock variable, the quantity of which is determined in order that the rate of growth of terminal investment is balanced.

Energy supply

Fossil fuel production levels are determined by the relative price of fuels and domestic output. The production of fuel f requires inputs of domestic supply and a fuel-specific factor of production which can be thought of as a sector-specific resource. The calibrated production function is written:

$$S_{rt}^{f} = \bar{S}_{rt}^{f}\left[\gamma\left(\frac{x_{rt}^{f}}{\bar{x}_{rt}^{f}}\right)^{\rho} + (1-\gamma)\left(\frac{R_{rt}^{f}}{\bar{R}_{rt}^{f}}\right)^{\rho}\right]^{1/\rho}$$

Due to the existence of a specific factor, energy supplies are determined by domestic prices in each period. The value of the elasticity of substitution between inputs x and the resource determines the price elasticity of supply at the reference point, according to the relation:

$$\eta = \sigma\frac{\gamma}{1-\gamma}$$

where $\sigma = 1/(1-\rho)$.